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METHOD FOR DETERMINING AN ORDER SEQUENCE FOR MANUFACTURING PLANTS
[VERFAHREN ZUR FESTLEGUNG EINER AUFTRAGSREIHENFOLGE FÜR FERTIGUNGSANLAGEN]

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Description

The invention relates to a method for determining an order sequence for manufacturing plants, in particular for vehicle production.

In automobile production, vehicle production occurs in several sequential steps: First the vehicle shells are built up from several pressed part assembly groups and subsequently painted. Then they are brought into the assembly area, where functional assembly groups such as chassis and axles and the special accessories depending on the model version such as sun roofs and electric windows are installed. The assembly takes place along sequential assembly lines and individual stations, where each specialized team implements specific assembly tasks.

Depending upon model variant, color, and accessories, a vehicle passing through the sheet metal shop, paint shop, and assembly area produces different machine utilizations and work load in the respective work stations. The sequence in which the models are channeled through these areas thus has decisive importance for the degree of utilization of the work stations. For optimization of total production costs, it is important to specify the order sequence in such a way that the degree of utilization of the paint lines, assembly lines, special assembly stations etc. is as uniform as possible and if possible close to 100%. The selection of the most favorable order sequence poses an extremely complex problem here:

Because of the large number of influence variables (model variant, color, special accessories etc.) and the complexity of the effects of the respective model mixes on the total utilization, monitoring of all boundary conditions and manual optimization of the assembly process are almost impossible.

The problem of determining optimized production parameters in a complex production process is known for example from US 5,229,948 and DE 196 43 884. DE 196 43 884 describes, using the example of a process for cellulose production in the paper industry, the optimization of process control by genetic algorithms. The task in this case is to find an optimal set of control variables which guides the production process to an optimal result. In contrast to DE 196 43 884, which is concerned with the optimization of competing control variables in a single process step, US 5,229,948 concerns the optimization of a multi-level, crosslinked production process with several buffer stations. For this purpose, a stochastic model is suggested, that is supposed to illustrate the entire production process and to explicitly include the contingent nature of some of the variables (for example machine availability) in the considerations. The goal of this method is to model the production process, in particular regarding optimization of the buffer stations. The order sequence plays only an secondary role here.

Further, the publication "Produktionsreihenfolgeplanung in Ringwalzwerken mit wissensbasierten und evolutionären Methoden"

["Production Sequence Planning in Ring Rolling Mills with Knowledge-Based and Evolutionary Methods"] (R. Mikut and F. Hendrich in at-Automatisierungstechnik 46, Oldenbourg Publishing House 1998, p 15-21) describes a solution approach to determination of an optimized order-oriented production sequence in a rolling mill. The individual production stages (rolling program, sawing program) are here regarded separately. Based on quality functions, which explicitly consider the restrictions of the respective production stage, with the help of evolutionary algorithms the optimal order sequence for this production stage is computed. Admittedly, the model suggested here does not define a factory-wide optimized order sequence, in which all production stages involved in the manufacturing process are considered in such a way that the total costs can be grasped and minimized over the entire sequential production process.

On the basis of this prior art, the present work pursues the objective of determining, for a multi-level, sequential, crosslinked production process, that order sequence that permits minimization of total costs. A realistic description and a relative weighting of the utilization goals of the different work stations involved in the process are therefore a central component and an important prerequisite for the problem underlying the present invention, of determining this optimal order sequence. On the other hand, the multiplicity of different restrictions which arise in the individual

production stages and which affect order sequence must be describable as uniformly as possible.

The invention is therefore based on the task of recommending a simple and flexible method for establishing a cost-optimized order sequence for manufacturing plants, in particular in automobile body production, automobile painting, and automobile installation which is based in quantitative and realistic models for the utilization goals of the individual plants and stations.

The task is solved according to invention by the features of Claim 1.

In accordance with this, first a set of features is assigned to each vehicle to be produced, which describes the requirements of this individual order on the manufacturing capacities to be made available. Such features include for example model, color, and engine installation of the vehicle as well as special options such as sun roof or air conditioning system etc. The associated manufacturing capacities include, for example, a suitable paint line in the paint shop, a suitable assembly line, as well as assembly team for the sun roof, air conditioning system etc.

In the compilation of an order sequence from a sequence of individual orders, for each feature there arises a feature sequence that has a direct influence on the utilization of the manufacturing capacities and resources needed for this feature. If the feature in this sequence at some points arises frequently, then this can lead to

overloading of the associated manufacturing capacities and resources. On the other hand, if the feature at some points of the sequence arises very rarely, then the associated manufacturing capacities and resources are not utilized. Both cases cause additional costs, for which reason they should be avoided during optimization of the order sequence if at all possible.

In order to be able to quantitatively grasp the costs connected with a frequent occurrence of a feature in an order sequence, it is appropriate to first compute an individual evaluation function for each feature, which represents a quality factor of the respective order sequence with respect to this feature. The individual evaluation functions are then combined into a total evaluation function for the totality of all features. This total evaluation function, called model mix quality, is appropriately formed by a weighted combination of the individual evaluation functions, whereby the relative weights of the individual functions represent the relative cost relevance of the individual features. The relative cost influences of different features can thus be very flexibly included in the modeling of the overall system.

For quantitative modeling of the cost influences of different features, the features are divided into two classes: space-oriented and density-oriented features.

With distance-oriented features, worker and/or plant capacities involved in this feature are disposed over a given minimum distance

at which the feature in the order sequence arises. If the feature in the order sequence appears at a smaller distance than this minimum distance, then the load on the involved workers and/or plants increases. The shorter the distance, the more cost-relevant this feature sequence as a rule, which is appropriately modeled by a non-linear increase in the weighting factors with a reduction in distance (see Claim 2). Some of the assembly features, in particular all comparatively rare special accessories (for example, installation of an air conditioning system, a sun roof, a brake assistant, a USA special package, an additional heating system needed for heavy diesel engines etc.) may be classed as distance-oriented features.

With the density-oriented features, on the other hand, the workers and/or plant capacities involved in this feature are disposed over a given maximum density with which the feature in the order sequence arises. If the feature appears in the order sequence with a higher density, then the load on the workers and/or plants increases during processing of the orders in an order block. With density-oriented features, the weighting factors are modeled appropriately in such a way that they increase linearly with an increase in feature density (see Claim 3). Typically those features which arise in the order sequence with a relatively high frequency are density-oriented. This includes for example, on the one hand, painting of the body, on the other hand the frequently arising assembly features such as series,

engine variant, automatic/manual transmission, color of seat covers etc.

The computation of the model mix quality according to invention with the help of the individual evaluation functions has the advantage that all cost-relevant factors which are affected by the order sequence can be evaluated concretely and flexibly. In particular, an evaluation of the order sequence can be made for each feature separately, into which empirically acquired cost values can flow simply and flexibly. Further, the relative weighting of the individual features in the model mix quality makes possible a simple strength assessment of particularly cost-relevant features, without ignoring the other features.

In the last step of the method according to invention, from the multiplicity of all (in principle) possible order sequences the one is finally selected which causes the smallest total costs, which is thus characterized by a minimum value of the model mix quality (see Claim 4). For calculation of this (optimal) order sequence, in accordance with Claim 5 the method of genetic algorithms is to be recommended: On the basis of several (arbitrary) output sequences these sequences are gradually changed, whereby for the production of a new sequence, on the one hand combinations of several previous sequences ("crossover"), and on the other hand also arbitrarily produced local changes ("mutations"), are allowed in the sequence. After each change of sequence, a check is made to determine whether

the newly developed sequence is "better" than the preceding. The evaluation of the quality of the sequence relative to other sequences is made with the help of a so-called fitness factor in such a way that the "optimal" sequence is characterized by a "best" fitness factor. In the present method to determine the most economical order sequence, the total evaluation function is appropriately used as the fitness factor

The method of genetic algorithms offers the advantage that in many cases it converges more quickly and reliably than other solution procedures and that it is also applicable to difficult optimization problems. It is particularly recommended therefore for the present complex problem of determining an order sequence which is optimal in terms of manufacturing logistics.

By suitable selection of the operators, with the help of which the "crossovers" are produced, the computational expenditure here can be kept small; a suitable implementation of the "mutations" ensures on the other hand that the entire phase space available to the system is searched and thus the "globally" optimal order sequence is found, instead of searching only a part of the phase space and to thus effecting a "local" optimization of the order sequence.

In the following the invention is explained with reference to an exemplary embodiment represented in the drawings, wherein:

Fig. 1 shows examples of different features,

Fig. 2 shows an order sequence consisting of 20 individual orders,

Fig. 3a shows a sequence of a distance-oriented feature,

Fig. 3b shows a weighting function of a distance-oriented feature,

Fig. 4a shows a sequence of a density-oriented feature,

Fig. 4b shows a weighting function of a density-oriented feature.

The following example is concerned with the use of the method according to the invention for determining the order sequence in the automobile industry. Each individual order corresponds to a vehicle which is to be manufactured. A set of features is assigned to each individual order, said set containing all the (ordering) information which is relevant for the manufacture of the vehicle from the manufacturing logistics standpoint. Examples of such features are for example the surface color (by which the paint requirement of the individual order is described), the model variant (which affects body manufacturing in the body production shop as well as preparation of a suitable assembly line), the special accessories (which presuppose the presence of the required assembly team and/or a procured part to be installed) etc. An excerpt from a table of these features is shown in Fig. 1.

An order sequence R_0 is arranged from the input individual orders. This order sequence R_0 corresponds for example to the succession of the vehicles to be manufactured on a certain day in an automobile plant. Fig. 2 shows an example of the first 20 individual orders of an order sequence R_0. The first individual order, shown on the far right and gray highlighted, corresponds to a white vehicle with 4-

speed transmission without special accessories. The 18th individual order, likewise grey highlighted, corresponds to a surf-blue vehicle with 5-speed transmission and electric windows. Additional individual orders are added from the left to the left end of the table, i.e. after that 20th individual order.

The typical number of individual orders which are processed in a large automobile plant in the course of a day lies between 1000 and 2000. In order to be able to produce the large number of vehicles which lie behind the individual orders economically, the sequence in which the individual orders go through the plant must fulfill certain requirements. Assuming that installation of an air conditioning system is a relatively time-consuming affair, the order sequence R_0 in Fig. 2 for example is not particularly favorable: Here the relatively time-consuming installation of an air conditioning system is demanded in three successive individual orders (No. 3, 4 and 5); in terms of manufacturing logistics this means that at this time either three air conditioning system assembly teams must be ready (which then admittedly later on in the order sequence R_0 possibly will not be working at full capacity for a long time), or that the vehicles corresponding to individual orders 4 and 5 must be put in a buffer station, where they will remain until the sole air conditioning system assembly team is finished with the installation of the air conditioning system in the vehicle of individual order 3. Both alternatives cause additional costs and are therefore unfavorable.

Therefore the need exists to re-sort the original order sequence R_0 shown in Fig. 2 in such a way that an economical as possible processing of individual orders results. The goal here is not to allow features to arise frequently but if possible to achieve the same distance or same density of the features. Depending on the properties connected with the features, in terms of manufacturing-logistics one differentiates between distance-oriented and density-oriented features:

Distance-oriented features are characterized by the fact that they arise relatively rarely in the individual orders. Thus for example, distance-oriented assembly features in the statistical average occur with a frequency of less than about 30%. In order to provide an individual order with a distance-oriented feature (an air conditioning system, for example), typically an assembly team and/or a manufacturing plant is required, which requires a specific time for implementation of this feature (for example installation), and therefore during this time is not available for further installation tasks. For example, as shown in Fig. 2, if several vehicles with air conditioning systems are supposed to be manufactured in rapid succession, this results in a high degree of utilization and/or overloading of the air conditioning system assembly team. In the extreme case, additional teams must be requested and/or the bodies in question must be diverted from the manufacturing stream. If the installation of an air conditioning system means a time expenditure

T_{klima} of 50 clock cycles, and only one air conditioning system assembly team is available, then under cost criteria it is favorable in each case to keep a distance of (at least) 50 vehicles in the order sequence between two individual orders which contain an air conditioning system. The optimal minimum distance i(opt) between successive occurrences of the distance-oriented feature "air conditioning system" thus as a value of 50. As long as this distance i(opt) is maintained, the air conditioning system assembly team, following the manufacturing stream, can install an air conditioning system in the first vehicle, and after completion of this assembly action, return to the starting point in the manufacturing chain and there take receipt of the next vehicle for installation of the air conditioning system.

Fig. 3a shows a excerpt from a individual order sequence R^A of distance-oriented feature A with minimum distance i(opt) = 5. At one point this sequence R^A has a distance = 4 between two individual orders which exhibit this feature A. This distance i is smaller than the optimal minimum distance i(opt), in which the workers and/or plants (with 100% utilization) are disposed, and during processing of the order sequence R^A leads to an increase of the load on the workers and/or plants. This load increment is all the more serious the more strongly the current distance i drops below the minimum distance i (opt). In the present example this load increment is modeled by a geometrical increase in the weighting function f^A(i, (opt)) with

diminishing distances i between two individual orders which exhibit this feature A (see Fig. 3b).

An individual evaluation function M^A of the distance-oriented feature A for the entire order sequence R^A is computed as the average value of all weightings which exhibit the feature A along this order sequence R^A. All distances i which are larger than the minimum distance i(opt), are assigned a load of 100%. The reason for this is that the capacity needed for the formation of the feature A (for example, the assembly team) is available even if a larger than ideal distance a i(opt) arises between two individual orders. The distances i which are smaller than the minimum distance i (opt) are assigned a load of i(opt)/i that is always greater than 100%. The individual evaluation function M^A is thus always ≥ 100%; it is the larger, the more frequently and/or more strongly the distance i falls below the minimum distance i(opt), and only takes the value of 100% when all distances i of the feature A in the order sequence are greater than or equal to the minimum distance i(opt).

If the frequency of the individual orders which exhibit the distance-oriented feature A (the air conditioning system, for example) on average is so high that a continuing overload of the assembly team occurs, then it can be favorable to make a second assembly team available, for which a minimum distance i(opt) should likewise be provided. Admittedly, this leads on the one hand to additional personnel costs, but on the other hand entails a reduction

in the individual evaluation function(s), since now on average for each assembly team the distance i between air conditioning systems to be installed is doubled in the order sequence. The individual evaluation function M^A thus closely correlates with the costs which are connected with the processing of a certain order sequence R^A.

In contrast to the distance-oriented features, the density-oriented features are characterized by the fact that they are required relatively frequently. Thus for example, density-oriented features appear in the statistical average with a frequency of more than 30%. In order to guarantee a high degree of utilization of the associated manufacturing stations (painting, assembly lines of individual series etc.), at these manufacturing stations drift areas are provided into which the vehicles planned for the respective feature are queued up. Thus for example in the paint line a color sort buffer is provided, from which the painting installations are supplied. These color sort buffers allow local rearranging and thus fine tuning of the filling sequence in order to allow an optimal degree of utilization of the painting stations (for example, in order to satisfy a rule valid for the optimal degree of utilization: "Five successive car bodies painted in the same color, followed by a color change"). In the interest of space and cost savings, the color sort buffers should be selected as small as possible. But in order that an even supply of the paint installations can be guaranteed nonetheless, these small buffers each time contain a sufficiently

large, but not too large number of car bodies which are to be painted the same color. This presupposes that for each color per time interval only a certain maximum number of car bodies arrive at the color sort buffers, i.e. that a certain maximum density of the (color) feature is not exceeded.

Fig. 4a shows a detail from a individual order sequence R^D of a density-oriented feature D, whose local density is computed by a means of a sliding block of length L = 7. The local density of the feature D corresponds to the frequency of the individual orders in the local block of the length L which exhibit this feature D. In the present case the maximum density of the feature D may lie at j(opt) /L = 4/7. As follows from Fig. 4a, this maximum density is exceeded at one point at which the local density amounts to j/L = 5/7. This increased density j/L leads to an overloading of the associated drift areas and is the more serious, the more strongly the local density j/L deviates from the maximum density j(opt) /L. In the present example this overload is modeled by a linear increase of the weighting function f^D(j, j (opt),L) with increasing local densities j/L at which the feature D arises in a block of length L (see Fig. 4b).

Analogously to the distance-oriented features, for the density-oriented feature D as well an individual evaluation function M^D of the order sequence R^D is calculated as the average value of all weightings which exhibit the feature D along this order sequence R^D. A load of

100% is assigned to all densities j/L which are smaller than the maximum density j(opt). This models the fact the drift area is made available for this feature D even if, per block length L, fewer car bodies of this feature D than expected arrive at the drift area. The densities j/L, which are larger than the maximum density j(opt) /L, are assigned a load of j/j(opt), which is always greater than 100%. The individual evaluation function M^D is thus always ≥ 100%. It is the larger, the more frequently and/or more strongly the density j/L exceeds the maximum value of j (opt) /L, and assumes the value 100% only when the local density j/L of the feature D everywhere in the order sequence R^D is less than or equal to the maximum density j (opt) /L.

Something similar is provided for the above-mentioned color sort buffers for the paint line, for the construction of the drift areas which are provided for the feed of the assembly lines of different series etc. The feature families "series," "engine variant" etc., which, relative to the complete order, arise with a comparatively high frequency (30% or more), so that their own manufacturing plants and/or assembly lines with the relevant drift areas are made available, are thus treated as density-oriented features.

The above-described modeling of the density or distance-oriented features with the help of a linear and/or geometrical trace of the load curves with elevated densities and/or too-small distances is not by any means the only possible description of behavior of these

features. Other functional dependencies of the load curves are conceivable, for example exponential increase in the load with too-small distances for distance-oriented features, or a non-linear increase of the load with too-large densities for density-oriented features. The choice of a suitable load curve for each individual feature (in particular, when experienced or measured variables are available for this) makes possible a quantitative, realistic, and transparent inclusion of the manufacturing costs associated with this feature in the general consideration of the order sequence.

In the given order sequence R_0, if for each density- or distance-oriented feature Z an individual evaluation function $M_0(Z)$ is defined (whereby for example for the distance-oriented feature A the function $M_0(A)$ possesses the value M^A, and for the density-oriented feature D the function $M_0(D)$ possesses the value M^D), the total evaluation function Γ_0 of this order sequence R_C can be calculated: It is formed as a linear combination of the individual evaluation functions $M_0(Z)$:

$$\Gamma_0 = \sum_{Z=1}^{Z=Max} (\gamma^Z \times M_0(Z)) \Big/ \sum_{Z=1}^{Z=Max} (\gamma^Z)$$

whereby "Max" designates the total number of features Z characterizing the order sequence R_0. The parameter γ^Z designates a weighting factor which describes the (cost-relevant) contribution of the feature Z to the total evaluation function Γ_0. For example, if the construction of a feature 21 requires a highly-qualified (and therefore highly-paid) assembly team or a machine with high operating

costs, then the weight factor γ^{Z1} subsumed with the associated individual evaluation function $M_0(Z1)$ in the total evaluation function Γ_0, is greater than the weight factor γ^{Z2} of a feature Z2, which is manufactured by a less cost-intensive assembly team and/or a more economical machine. The weighting factors γ^Z can thus be adapted to the cost situation in the manufacturing of the individual features Z.

The total evaluation function Γ_0 is a measure of how "economically" the order sequence R_0 can be manufactured: In the financially most favorable case, i.e. when for each feature Z the individual evaluation function amounts to $M_0(Z) = 100\%$ (thus when not a single density or distance violation occurs in the feature sequences), the total evaluation function assumes the value $\Gamma_0 = 100\%$. Each density and/or distance violation of the features leads to an increase of the associated individual evaluation functions and thus to a total evaluation function $\Gamma_0 > 100\%$. In this case, on the basis of the (randomly compiled) initial order sequence R_0, the optimal order sequences R_{opt} are found which lead to a minimum value of the associated total evaluation function Γ_{opt}. This minimum value should lie as close as possible to 100%.

For determination of the optimal order sequence R_{opt}, the method of genetic algorithms is appropriately used: Each order sequence R hereby corresponds to an individual. A population of such individuals is randomly produced, and the "fitness factor" of each individual determined by calculation of the total evaluation function G_R of the

associated order sequence R. described above. Subsequently, in particular the following evolutionary step is repeatedly accomplished: Three individuals are selected from the population. That individual of these three who has the worst "fitness factor" is removed from the population and replaced by a combination of the two better ones (whereby, depending one the type and weighting of the features in the order sequence R, the combination can be variously adapted). In the sense of evolution by means of the genetic algorithms, therefore, the population is constantly improved. The process is curtailed when the "fitness factor" (i.e. the associated total evaluation function) reaches a previously specified goal value, or when the "fitness factor" reaches saturation and can no longer be improved by further evolutionary steps.

Claims

1. A method to determine an order sequence for manufacturing plants, in particular for manufacturing plants in automobile construction, whereby the order sequence consists of a sequence of individual orders,

- whereby each individual order is characterized by a set of technical features which describes the requirements of this individual order on the manufacturing capacities to be made available,

- whereby to evaluate a given order sequence, an individual evaluation function is first assigned to each feature,

- and whereby finally, from the plurality of possible order sequences, that one is selected which is distinguished by a given value of the total evaluation function,

- whereby to determine the individual evaluation functions, each feature is characterized as either distance-oriented or density-oriented,

- and whereby the individual evaluation functions M^A of a distance-oriented feature A is calculated as follows:

$$M^A = \left[\sum_{i=1}^{i=MAX} n_i * f^A(i, i(opt))\right] / \left[\sum_{i=1}^{i=MAX} n_i\right]$$

- whereby MAX is the number of individual orders in the given order sequence,

- whereby n_i indicates how frequently in the given order sequence the distance between two successive occurrences of the distance-oriented feature A assumes the value i,

- whereby i(opt) is the optimal minimal distance, in terms of manufacturing logistics, between two successive occurrences of the distance-oriented feature A,

- and whereby $f^A(i, i(opt))$ is the weighting function of the distance-oriented feature A;

- while the individual evaluation function M^D of a density-oriented feature D is calculated as follows:

$$M^D = \left[\sum_{j=1}^{j=L} n_j * f^D(j, j(opt), L)\right] / \left[\sum_{j=1}^{j=L} n_j\right]$$

- whereby L designates the length of a block of orders over which the density of the feature D should be calculated,

- whereby n_j indicates how frequently it occurs in the given order sequence that in an order block with L successive orders, the feature D is represented precisely j times,

- and whereby $f^D(j, j(opt))$ is the weighting function of the density-oriented feature D.

2. The method according to Claim 1, characterized in that the weighting function $f^A(i, i(opt))$ of the distance-oriented feature A assumes the following functional form:

$f^A(i, i(opt)) = i(opt)/i \cdot 100\%$ for $1 \leq i \leq i(opt)$

$f^A(i, i(opt)) = 100\%$ for $i(opt) < i \leq MAX$.

3. The method according to Claim 1, characterized in that the weighting function $f^D(j, j(opt), L)$ of the density-oriented feature D assumes the following functional form:

$f^D(j, j(opt), L) = 100\%$ for $1 \leq j \leq i(opt)$

$f^D(j, j(opt), L) = j/j(opt) \cdot 100\%$ for $j(opt) \leq j \leq L$.

4. The method according to Claim 1, characterized in that from the plurality of possible order sequences, those are selected which are distinguished for a minimal value of the individual evaluation function.

5. The method according to Claim 1, characterized in that general algorithms are used to provide and/or evaluate the order sequences

whereby the individual evaluation function is utilized as a fitness function.

Four pages of drawings follow.

Feature 1:	paint color signal red
Feature 2:	pain color metallic bordeaux red
Feature 3:	paint color surf blue
Feature 4:	paint color metallic night blue
Feature 5:	paint color white
. . .	. . .
Feature i:	4-speed transmission
Feature i+1:	5-speed transmission
Feature i+2:	4-speed automatic transmission
Feature i+3:	5-speed automatic transmission
. . .	. . .
Feature n:	electric windows
Feature n+1:	air conditioner
Feature n+2:	sun roof
Feature n+3:	radio telephone

FIGURE 1

<----------------------------

------------------Order Sequence---------------------------------------

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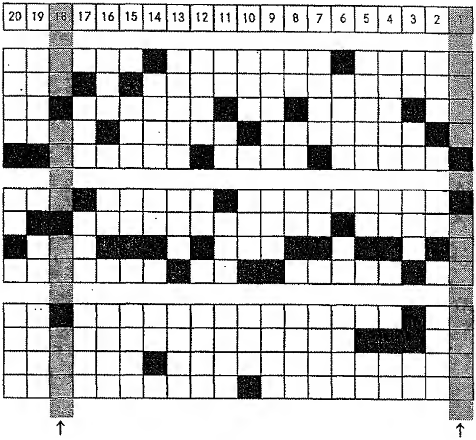
No. of individual

order:

Merkmal = feature



18th Order

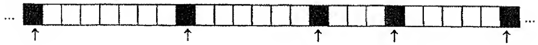
1st Order

- Feature included in order

- Feature not included in order

FIGURE 2

Sequence of distance-oriented feature "sun roof"



[Abstand = distance]

FIGURE 3A

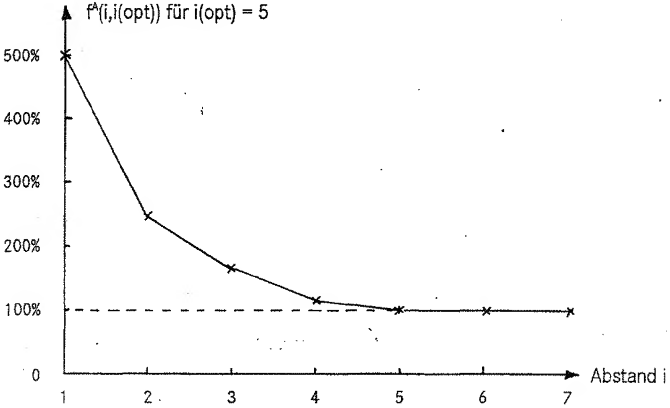
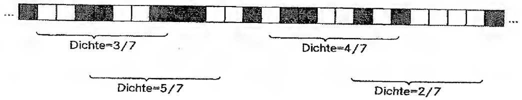


FIGURE 3B

Sequence of density-oriented feature "signal-red paint color" with block-length of L = 7.



[Dichte = density]

FIGURE 4a

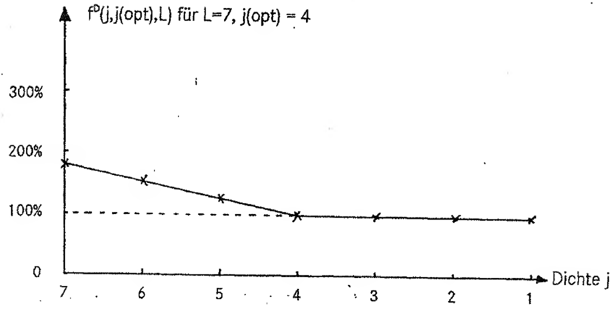


FIGURE 4b